Journal of Engineering Physics and Thermophysics, Vol. 80, No. 4, 2007

TEMPERATURE MECHANISMS OF THE INTERACTION OF DISLOCATIONS WITH IMPURITIES IN THE PROCESSES OF TRANSFER OF THE ENERGY OF ELASTIC VIBRATIONS

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UDC 519.6:536

The influence of microplasticity caused by the motion of dislocation segments on the propagation of elastic vibrations in structural materials is considered. It is shown that the character of motion of a dislocation segment exerts its effect on the propagation velocity of an acoustic wave. This fact should be taken into account when nonstationary frequency-phase methods of measuring the physical parameters of a medium are used.

Introduction. As is known, in structural materials, in order to impart certain service properties to them such as, e.g., high-temperature strength, elasticity, wear resistance, etc., a definite type of defect structure is being formed, which also includes extensive and point defects that make it possible either to stabilize the position of dislocations in space or permit their displacement in close margins, thereby imparting certain properties relating to the hardness, brittleness, and elasticity of the materials. At the same time, the propagation of ultrasonic vibrations is influenced by microplasticity, which enhances dissipative processes. Moreover, even an insignificant displacement of dislocation segments in the field of the stresses of a wave leads to a partial irreversible deformation with a loss of elastic properties and a decrease in the velocity of ultrasound. In application to nonstationary frequency-phase methods of measuring the physical parameters of the medium which are based on the tracing of changes in the difference of phases between the sounding and reference ultrasonic waves, the indicated change in the velocity of sound is to be additionally taken into account [1, 2]. Here, we consider some characteristic features of the behavior of a dislocation segment exposed to the effect of an alternating stress of low and intermediate frequency with allowance for the effect of temperature mechanisms on elastic interaction of substitutional impurities with dislocations in the atmospheres of point defects. The contribution of the indicated processes to the phenomenon of microplasticity has been analyzed with the example of the propagation of the energy of elastic vibrations.

Statement of the Problem and Its Solution. The threshold stresses of the onset of microplasticity as a result of the operation of dislocation segments according to the Frank–Reed model on alternating loading represent a certain analog of the yield point on static loading. The irreversibility of microscopic deformation as an indicator of plasticity at any type of loading is associated with the motion of already available dislocations as well as with the possibility of generation of new dislocation loops by a fixed source. The well-known principles of the dynamics of a dislocation segment in describing internal friction in the approximation of a string model [3–5] have been adapted within the framework of the present problem to the problem of allowance for not only inertial, viscous, and elastic forces, but also for additional forces of interaction with impurity atoms. As is known, impurities form atmospheres around extensive defects, and the motion of dislocations depends on the species and size of foreign interstitial and substitutional atoms.

As an initial approximation in consideration of the problem, a string model of the dynamics of a dislocation segment with a modified right-hand side has been selected. In accordance with further development, by Swartz and Virtman, of Koehler–Granato–Lucke's theory of the absorption of the energy of elastic vibrations, a dislocation in a material experiences the action of the force that prevents its displacement, i.e., the force directed opposite to the stress applied [6, 7]. This force owes its origin to the presence of the binding energy between the edge dislocation and an

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impurity atom from the atmosphere surrounding this dislocation. The magnitude and sign of the binding energy are determined by the distance between the impurity atom and the dislocation core, as well as by its position relative to the extraplane, respectively. A large part is played here by the difference between the sizes of impurity atoms and the atoms of the material. On the other hand, the very quantity or concentration of impurity atoms near a dislocation and their Friedel distribution are prescribed by the sign of the binding energy and by the ratio of this energy to the characteristic energy of thermal vibrations which enters in the so-called Boltzmann factor.

As a first approximation we selected the following model: in a metallic material the impurity atoms are predominantly substitutional atoms with radii exceeding those of base atoms. They are attracted to the region located under the extraplane, and in these positions they possess a negative binding energy. Consequently, on exposure to an external alternating elastic stress such atoms will prevent the motion of the segment. This means that in such an approach the value of the amplitude of the external stress decreases effectively. Then it is advisable that the differential equation which describes small-amplitude vibrations of the segment in the field of the given alternating stress be represented as follows:

$$A\frac{\partial^2\zeta}{\partial t^2}+B\frac{\partial\zeta}{\partial t}-C\frac{\partial^2\zeta}{\partial y^2}=\left[b\sigma-\frac{bG\xi c_{\mathrm{i}}}{4}\exp\left(\frac{W}{kT}\right)\right]\sin\omega t\,. \qquad (1)$$

Here $A = \rho b^2/\pi$ is the effective mass of dislocation per its unit length; $C = \frac{2Gb^2}{\pi(1-\nu)}$ is the coefficient which determines the elastic self-action of the segment on its extension; $b\sigma$ is the amplitude value of the alternating stress, reduced to the dislocation length in the acoustic wave field; $\xi = \frac{R_{\mathrm{i}}-R_{\mathrm{b}}}{R_{\mathrm{b}}}$ is the relative difference of the radii of impurity atoms (R_{i}) and those of the basic material (R_{b}); $W(r) = \frac{GbR_{\mathrm{b}}\xi(1+\nu)\sin\theta}{3\pi(1-\nu)r}$ is the energy of binding of the segment with the impurity atoms in the Cottrell atmosphere with account for their position relative to the extraplane. In further calculations, the effective stress of elastic interaction of impurities with the dislocation segment, which partially compensates the action of the external alternating stress, will be designated as $D = \frac{C\xi c_{\mathrm{i}}}{4}\exp\left(\frac{W}{kT}\right)$.

In order to solve Eq. (1) we will apply an operational method which implies direct and inverse integral transformation in accordance with the expressions

$$\bar{\zeta}(y,s)=\int_0^\infty \zeta(y,t)\exp(-st)\,dt\,,$$

$$\zeta(y,t)=\frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty}\bar{\zeta}(s,t)\exp(st)\,ds\,. \qquad (2)$$

In the course of transformation one should perform direct and inverse transformation of variables $\omega t \to t' \to t$, which allows one to reduce the partial differential equation (1) to an ordinary second-order inhomogeneous algebraic equation with constant coefficients for integral Laplace images:

$$\frac{d^2\bar{\zeta}}{dy^2}-\frac{A\omega^2s^2+B\omega s}{C}\bar{\zeta}=-\frac{A\omega^2s+B\omega}{C}\zeta(t=0)-\frac{A\omega^2}{C}\frac{d\zeta(t=0)}{dt}-\frac{b(\sigma-D)}{C}\frac{1}{1+s^2}\,. \qquad (3)$$

Applying the method of variation of the Lagrange arbitrary constant to Eq. (3), we obtain an expression for the local shift of the segment from the equilibrium position along its length:

$$\bar{\zeta}(y,s)=D_1\exp(\Omega y)+D_2\exp(-\Omega y)+$$

$$+\left[\frac{A\omega^2 s+B\omega}{C}\zeta(t=0)+\frac{A\omega^2}{C}\frac{d\zeta(t=0)}{dt}+\frac{b(\sigma-D)}{C}\frac{1}{1+s^2}\right]\frac{C}{A\omega^2 s^2+B\omega s}\,. \tag{4}$$

Here $\Omega=\left(\frac{A\omega^2 s^2+B\omega s}{C}\right)^{1/2}$ and D_1 and D_2 are the integration constants which are to be found using realistic boundary conditions. To calculate D_1 and D_2 we apply the condition of zero displacement of the segment at its pinning points for both the direct time and the inverse one after the Laplace transformation.

As a result, we obtain

$$\bar{\zeta}(y,s)=\left[-\frac{\exp(\Omega y)+\exp(-\Omega y)}{\exp(\Omega y)-\exp(-\Omega y)}+1\right]\times$$
$$\times\left[\frac{A\omega^2 s+B\omega}{C}\zeta(t=0)+\frac{A\omega^2}{C}\frac{d\zeta(t=0)}{dt}+\frac{b(\sigma-D)}{C}\frac{1}{1+s^2}\right]\frac{C}{A\omega^2 s^2+B\omega s}\,. \tag{5}$$

The area covered by the dislocation segment in the process of vibration under the action of an alternating force determines the degree of its readiness to come into action when the central part attains a certain critical displacement from the equilibrium position. For the convenience of analyzing and considering the combined nonequilibrium state of the segment, as the next step it is advisable to determine the length-averaged displacement via summation of local contributions:

$$\langle\bar{\zeta}(s)\rangle=\frac{1}{2l}\int_{-l}^{l}\bar{\zeta}(y,s)\,dy\,. \tag{6}$$

Integration of (5) according to Eq. (6) yields the length-averaged displacement which is a parameter depending only on the variable for integral transformation of s:

$$\langle\bar{\zeta}(s)\rangle=\left[-\frac{\exp(\Omega l)+\exp(-\Omega l)}{\exp(\Omega l)-\exp(-\Omega l)}\frac{1}{\Omega l}+1\right]\times$$
$$\times\left[\frac{1}{s}\zeta(t=0)+\frac{A\omega^2}{A\omega^2 s^2+B\omega s}\frac{d\zeta(t=0)}{dt}+\frac{b(\sigma-D)}{A\omega^2 s^2+B\omega s}\frac{1}{1+s^2}\right]. \tag{7}$$

After having performed the procedure of inverse integral transformation similarly to Eq. (2) with application of contour integration for the functions of a complex variable and of the theory of residues, we determine the average displacement of the dislocation segment as a function of time as follows:

$$\langle\zeta(t)\rangle=\frac{b(\sigma-D)\,l^2}{3C}\left[\frac{\exp(i\omega t)}{2i\left(1+\frac{i\omega Bl^2}{2C}\right)}-\frac{\exp(-i\omega t)}{2i\left(1-\frac{i\omega Bl^2}{2C}\right)}+\frac{\exp\left(-\frac{2C}{Bl^2}t\right)}{\left(1+\frac{4C^2}{\omega^2B^2l^4}\right)\frac{\omega Bl^2}{2C}}\right]. \tag{8}$$

According to Eq. (8), the average displacement of the dislocation of the segment has an oscillating component as well as a relaxation-type component. Such a solution complies with the presence of the process of transition and with the motion established at a frequency of an exciting external force. As numerical estimates show, the characteristic time of relaxation $Bl^2/2C$ for a wide range of metals attains a value on the order of 10^{-1}–10^{-5} sec. Consequently, during a small period after the application of external loading the transient processes with the

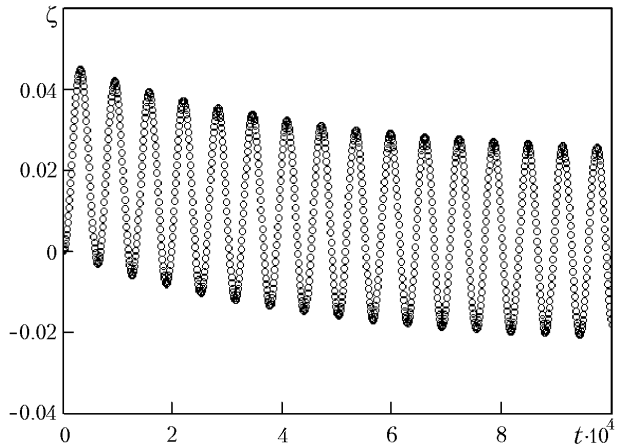

Fig. 1. Average displacement of a segment of length $l = 10^{-4}$ m as a function of time. $G = 4 \cdot 10^{10}$ Pa, $\nu = 0.3$, $B = 5 \cdot 10^{-4}$ Pa·sec, $\rho = 2.7 \cdot 10^{3}$ kg/m^3, $b = 4 \cdot 10^{-10}$ m, $\omega = 10^5$ rad/sec. ζ, rel. units; t, sec.

relaxation time $Bl^2/2C$ are completed and only asymptotic values of the parameters typical of forced vibrations of the segment remain. Then the asymptotically averaged displacement along the length can be presented as a function of time in the form

$$\langle \zeta (t) \rangle = \frac{b(\sigma - D)\, l^2}{3C} \left\{ \frac{\exp(i\omega t)\left(1 - \dfrac{i\omega B l^2}{2C}\right) - \exp(-i\omega t)\left(1 + \dfrac{i\omega B l^2}{2C}\right)}{2i\left[1 + \left(\dfrac{\omega B l^2}{2C}\right)^2\right]} \right\}, \tag{9}$$

which, using Euler's equations, can be easily reduced to expressions containing trigonometric functions:

$$\langle \zeta (t) \rangle = \frac{b(\sigma - D)\, l^2}{3C} \left[\frac{\sin(\omega t) - \dfrac{\omega B l^2}{2C}\cos(\omega t)}{1 + \left(\dfrac{\omega B l^2}{2C}\right)^2} \right]. \tag{10}$$

In expression (10), the length-averaged displacement of the segment contains two components: that coinciding in phase with a perturbing force and that $\pi/2$ out of phase. The component of the segment displacement that is in-phase with the driving force corresponds to a pure dissipationless motion of the segment, whereas the out-of-phase-motion component determines the weight of the forces of viscous friction. Formally, when the coefficient of dynamic viscosity strives toward a large quantity, the expression for the amplitude of displacement may be reduced to the form

$$\langle \zeta (t) \rangle = -\frac{2b(\sigma - D)}{3\omega B}\cos(\omega t)\,. \tag{11}$$

From Eq. (11) it follows that in the presence of high viscous forces the displacement amplitude averaged over the segment length will be insignificant.

Discussion of Results and Analysis of the Relations Obtained. Figure 1 shows the length-averaged displacement of the segment as a function of time for the range of frequencies of the order of hundreds of kHz. As is seen from the figure, for a segment of length 10^{-2} cm the regime of established vibrations sets in on a lapse of 0.001 sec after application of loading or after the arrival of the ultrasonic wave front.

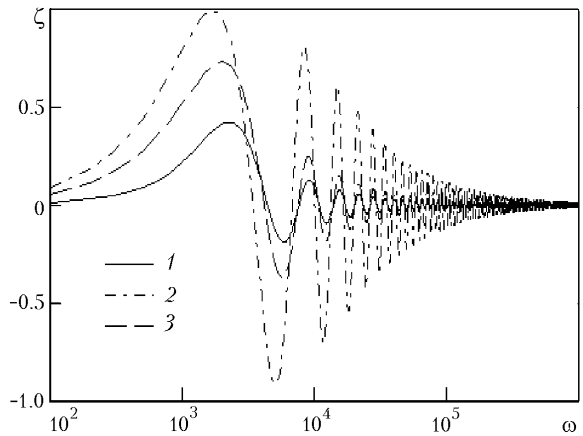

Fig. 2. Average displacement of a segment of length $l = 10^{-4}$ m depending on frequency at $t = 0.001$ sec: 1) $B = 10^{-3}$; 2) 10^{-4}; 3) 10^{-5} Pa·sec. G, $4 \cdot 10^{10}$ Pa, $\nu = 0.3$, $\rho = 2.7 \cdot 10^3$ kg/m^3, $b = 4 \cdot 10^{-10}$ m. ζ, rel. units; ω, rad/sec.

The dependence of the averaged displacement of such a segment at time $t = 0.001$ sec at different values of viscosity force is presented in Fig. 2. According to the general principles, an increase in the frequency of an ultrasonic field at a considerable level of viscosity forces leads to a decrease in the averaged displacement and to an oscillating change of the phase. The figure shows the undesirable range of frequencies the vibrations at which lead to elevated levels of plastic deformation.

On the basis of expression (10), applying the traditional scheme of calculation, we may determine the change in the rate of elastic vibrations. Under the conditions of an elastic medium, the equation of a wave is written as

$$\frac{\partial^2 \sigma}{\partial x^2} - \rho \frac{\partial^2 \varepsilon}{\partial t^2} = 0 , \tag{12}$$

where ε is the deformation, which, with account for plasticity, can be represented as a sum of elastic and plastic components: $\varepsilon = \varepsilon_{el} + \varepsilon_{pl}$, $\varepsilon_{pl} = \frac{\Lambda}{V} \langle \xi(t) \rangle b$, $\frac{\Lambda}{V}$ being the density of dislocations. Taking this into account, the wave equation will take the form

$$\frac{\partial^2 \sigma}{\partial x^2} - \frac{\rho}{G} \frac{\partial^2 \sigma}{\partial t^2} = \frac{\partial^2}{\partial t^2} \left[\frac{\Lambda}{V} \langle \zeta (t) \rangle \, b \right]. \tag{13}$$

Using the expression for the amplitude of displacement of the dislocation segment in the form

$$\langle \zeta \rangle = \frac{b (\sigma - D) \, l^2}{3C} \frac{\frac{\omega B l^2}{2C}}{1 + \left(\frac{\omega B l^2}{2C} \right)^2} \tag{14}$$

and (13), we obtain an equation for the speed of an elastic wave:

$$\upsilon = \sqrt{\frac{G}{\rho}} \left[1 - \frac{1}{2} \frac{\Lambda}{V} \frac{\rho b^2 l^4}{C^2} \frac{B\omega}{1 + \left(\frac{B \omega l^2}{2C} \right)^2} \right]. \tag{15}$$

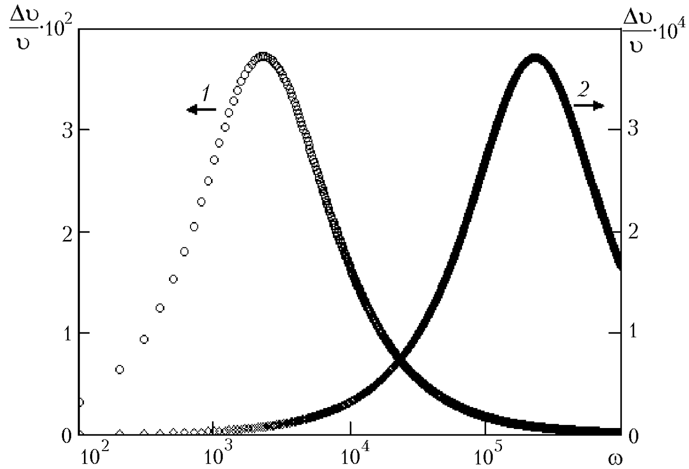

Fig. 3. Relative change in the velocity of propagation of elastic vibrations as a function of frequency for sections of different lengths: 1) $l = 10^{-4}$; 2) 10^{-5} m. ω, rad/sec.

The dependence of the relative change in the velocity on frequency (Fig. 3) reveals an extremum that is a consequence of the joint action of two factors that were considered when the results of calculations were discussed (see Figs. 1 and 2). The depth of the extremum shows the range of change in velocity and its coupling with the medium parameters. It is seen that the magnitude of the extremum is proportional to the squared length of the segment. Thus, for a section of length 10^{-4} m it amounts to about $4 \cdot 10^{-2}$ and for 10^{-5} m to about $4 \cdot 10^{-4}$. The position of the extremum is shifted in this case to the region of higher frequencies. Physically this means that at low frequencies on a relatively large displacement of the segment the phenomenon of microplasticity exerts a stronger effect on the segment than at high frequencies. In the region of high frequencies with a small amplitude of displacement, the contribution of dynamic plastic deformation becomes insignificant, especially for short dislocation segments.

It should be noted that elastic moduli are themselves weak functions of temperature, and even in the approximation of a static loading the amplitude of the displacement of a dislocation segment changes little with temperature. Calculation by Eq. (14) showed that the relative change in the displacement amplitude with such an approximation in the temperature range 100–500 K does not exceed 1%. Allowance for the interaction of the dislocation segment with impurity atoms resulted in the displacement amplitude at low temperatures becoming more sensitive to the distribution of impurities in the region of the segment, whereas in the region of high temperatures the presence of nonequilibrium configurations of impurity atoms affects the dynamic properties of the segment to a lesser degrapostropue. This is due to the fact that at low temperatures the concentration of impurity atoms in Cottrell's and Snoek's atmospheres increases up to their saturation and precipitation of individual new phases, whereas with an increase in temperature the clouds of the atmospheres of impurity atoms near dislocations are scattered right up to the attainment of equilibrium concentration typical of the region far from extensive defects. We note that regardless of the type of impurities with respect to the sizes of their atoms relative to the inherent atoms one should select a negative energy of interaction in the sense that the substitutional impurities with atoms larger than the inherent ones will diffuse and settle under the dislocation extraplane, whereas the substitutional impurities with atoms smaller than the inherent ones will diffuse and settle in compression regions, i.e., above the dislocation extraplane. For this reason, in the first approximation, when analyzing the values of the binding energy of impurities with dislocation it is advisable to select values for the azimuthal angle and distances of an impurity atom to the extraplane that would correspond to the maximum binding energy in absolute value, with it being negative in sign.

A change in temperature exerts its effect on the motion of the dislocation section in two ways, viz., via the coefficient of dynamic viscosity, which at temperatures on the order of magnitude of the Debye temperature or higher is a linear function of temperature, on the one hand, and via the elastic forces of interaction of the segment with impurities in the far-range stress fields, on the other hand.

In order to estimate the combined effect of temperature mechanisms on time-alternating loading, it is necessary to carry out a numerical experiment on modeling the effect of the above-cited factors on the behavior of a model dislocation segment of different lengths. And at the level of phenomenological correction parameters it is necessary to take into account the factor of great deviations from the equilibrium of the segment and the finite rate of collapse of the segment on attainment of critical bends. It is advisable to carry out correction using the techniques of consideration of the Frank–Reed source on finite-constant loading.

NOTATION

b, Burgers vector, m; B, coefficient determining the force of dynamic viscous friction, Pa·sec; c_i, volumetric equilibrium concentration of impurities far from the dislocation segment, m^{-3}; G, elastic rigidity modulus, Pa; k, Boltzmann constant, J/K; l, length of the dislocation section, m; r, distance from the dislocation core to an impurity atom, m; R_i, radius of an impurity atom, m; R_b, radius of an inherent atom, m; s, parameter of integral transformation; t, time, sec; T, absolute temperature, K; V, volume, m^3; W, energy of binding of the dislocation segment with impurity atoms, J; x, direction of propagation of an acoustic wave, m; y, direction along the length of the dislocation segment, m; ε, deformation; ε_{pl} and ε_{el}, plastic and elastic components of deformation; θ, azimuthal angle between the Burgers vector and the radius-vector of an impurity atom, rad; Λ, total length of dislocation segments in a volume V, m; ν, Poisson coefficient; ρ, density of a substance, kg/m^3; ζ, value by which a dislocation segment shifts from the equilibrium position along its length, m; σ, amplitude value of the alternate pressure in the acoustic wave field, Pa; ω, cyclic frequency of elastic vibrations, rad/sec; υ, velocity of elastic wave propagation, m/sec. Subscripts: i, impurity; b, basic; pl, plastic; el, elastic.

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